A Large Underground Liquid Argon Detector without a Cryostat

Kirk T McDonald (kirkmcd@princeton.edu)
Princeton University
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Introduction

The construction of a large liquid argon detector on the Earth's surface is advantageous because of the extensive experience of the liquefied natural gas industry in low-cost fabrication of cryogenic tanks of order of 100 kton. However, fabrication of this type of tank in an underground cavern is likely to be prohibitively expensive. Here, we note that the thermal conductivity of granite is low enough that a large, uninsulated cavity filled with liquid argon leads to thermal losses very similar to those of a cryogenic tank on the surface.

Heat Flow in a Large Cavity Filled with Liquid Argon

For simplicity, we consider a spherical cavity of radius r_0 that has been excavated out of granite, whose thermal conductivity is $\kappa = 2.2$ W/m-K and whose equilibrium temperature is $T_\infty \approx 300°$. The cavity is filled with liquid argon whose temperature is $T_0 \approx 87°$. The temperature difference $T_\infty - T_0$ results in a spherically symmetric temperature distribution $T(r)$ and a corresponding heat flow dQ/dt into the liquid argon.

The steady state temperature distribution obeys $\nabla^2 T = 0$, so for $r > r_0$ it has the form $T(r) = T_\infty - (T_\infty - T_0) r_0 / r$. The rate of heat flow across a (vector) area element $\mathbf{A}$ is $dQ/dt = -\kappa \nabla T \bullet \mathbf{A}$. Since $\nabla T = -(T_\infty - T_0) r_0\, \hat{\mathrm{r}} / r^2$, the total rate of heat flow into the sphere of radius r_0 is $dQ/dt = 4\pi\kappa(T_\infty - T_0) r_0$.

For example, if $r_0 = 20$ m, then the mass of liquid argon in the cavity is 50 ktons, and $dQ/dt = 4\pi(2.2)(300 - 87)20 \approx 120$ kW. As the heat of vaporization of argon is 160 kJ/kg, this heat flux will vaporize 0.75 kg/s, *i.e.*, 66 tons/day, or 0.13%/day of the detector mass. This rate is very similar to that quoted as the rate of vaporization of a surface cryogenic tank.

Hence, it appears that an uninsulated, underground granite cavity is as good a cryogenic vessel as a typical large surface tank of the liquefied natural gas industry.

Operational Issues

We comment briefly on issues that deserve further study as to the viability of operating an uninsulated, liquid-argon-filled cavity underground.

The heat load of 120 kW at $87°$ K must be compensated by a refrigerator operating between $87°$ K and $\approx 300°$ K. If the efficiency of the refrigerator is, say, 12%, then 1 MW of wall power is required.

Outside a cavity with $r_0 = 20\,\text{m}$, the temperature varies as $300° - 4260°/r$. The temperature reaches $0°\,\text{K}$ only at $r = 185\,\text{m}$. Any tunnels closer than this to the cavity would have to be heated if/when they are to be used by people.

Cold granite is, I believe, stronger than warm granite, so the rock surrounding the cold cavity is somewhat more robust against collapse than when warm.

The cavity would, of course, have to be lined with some material that is impermeable to the flow of liquid argon.

Should the liner have a leak, some liquid argon would boil off into the surrounding environment, leading to an oxygen-deficiency hazard. If the cavity is designed so that the surrounding tunnels (whose walls are cold unless heated) form a trapped volume whose surface area is similar to that of the cavity (say 500 m of tunnels of 3-m diameter), the rate of vaporization of argon due to a leak would be less than or equal to that calculated above, namely 66 tons/day. In this case it would take over 2 years for the entire 50 ktons of liquid argon to vaporize. Of course, a boiloff of 66 tons/day would lead to $\approx 40,000\,\text{m}^3$ of argon gas at $300°\,\text{K}$, which still constitutes a significant safety hazard unless properly ventilated.

Compatibility with a Large Magnet Coil

The simplicity of construction of a large liquid argon detector in an uninsulated, underground cavity is compatible with installation of a large magnet coil close to the surface of the cavity, inside the liquid argon. If this coil were superconducting, the liquid argon would serve as an intermediate temperature bath in place of the more typical use of liquid nitrogen. Furthermore, a giant magnet coil would require radial buttressing against the cavity wall to contain the expansive $\mathbf{I} \times \mathbf{B}$ forces, which buttressing could be readily accommodated in the design of an uninsulated cavity.